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16. ABSTRACT

The paper gives results of tests of two commercially available water-in-oil emulsifiers to determine the effect of water/residual oil emulsions on air pollutant emissions and thermal efficiency of a packaged boiler. Of the two emulsifiers, one (Cottell reactor) utilized low pressure mechanical and ultrasonic energy and the other (Total emulsifier) utilized high pressure mechanical energy. Each emulsifier was tested at a constant oil flow rate with varying amounts of water over a range of stoichiometric ratios. Water/residual oil emulsions from both emulsifiers significantly reduced particulate mass. With the Cottell reactor smoke emissions were significantly reduced, whereas with the Total emulsifier smoke emissions increased and peaked with a 20 percent water emulsion, then decreased as water was increased to 30 percent. Neither emulsifier had any significant effect on emissions of NO, SO2 or HC when firing water/residual oil emulsions. Both emulsifiers were capable of improving efficiency by approximately 2 percent under certain conditions.

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Emulsifying Agents	Stationary Sources	11G
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The Effect of Water/Residual Oil Emulsions on Air Pollutant Emissions and Efficiency of Commercial Boilers

Two commercially available water-in-oil emulsifiers were tested to determine the effect of water/residual oil emulsions on air pollutant emissions and thermal efficiency of a packaged boiler. Of the two emulsifiers, one (Cottell reactor) utilized low pressure mechanical and ultrasonic energy and the other (total emulsifier) utilized high pressure mechanical energy. Each emulsifier was tested at a constant oil flow rate with varying amounts of water over a range of stoichiometric ratios. Water/residual oil emulsions from both emulsifiers significantly reduced particulate mass. With the Cottell reactor smoke emissions were significantly reduced, whereas with the Total emulsifier smoke emissions increased and peaked with a 20 percent water emulsion, then decreased as water was increased to 30 percent. Neither emulsifier had any significant effect on emissions of NO, SO_2, or HC when firing water/residual oil emulsions. Both emulsifiers were capable of improving efficiency by approximately 2 percent under certain conditions.

Introduction

In recent years there has been much interest in the effect of water-in-oil emulsions on air pollutant emissions and efficiency of commercial packaged boilers. As part of an ongoing in-house project, the Industrial Environmental Research Laboratory of the U. S. Environmental Protection Agency[1] has studied the effect of water/residual oil emulsions on the emissions of nitric oxide (NO), carbon monoxide (CO), unburned hydrocarbons (HC), smoke, and particulate. The effect of emulsions on thermal efficiency has also been investigated.

Two commercially available emulsion systems were chosen for evaluation. One was a low pressure device which utilized ultrasonic emulsification (Cottell reactor)[2] and the other was a mechanical device which utilized high pressure emulsification (total).[3] Both are designed to be installed in the fuel supply line ahead of the nozzle and require a minimum of installation time.

Background

In the early 1960's Ivanov and Nefedov [1][4] of the USSR reported that emulsions burn faster, improve combustion, and reduce soot formation. In the late 1960's, Barrett, et al. [2, 3] of Battelle Columbus Laboratories performed preliminary tests with water/oil emulsions under contract to the National Air Pollution Control Administration (a predecessor of EPA). In 1973, Turner and Siegmund [4] reported test results showing that emulsions reduce thermal NO_x but do not reduce fuel related NO_x. More re-

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[2] Manufactured by Crest Ultrasonics Corp., Scotch Road, Mercer County Airport, Trenton, N. J. 08628.

[3] Manufactured by Compagnie Francaise de Raffinage, 39-43 Quai Andre-Citroen, 75739 Paris Cedex 15, France. The U. S. representative is D. S. Volkmar, 610 Fifth Avenue, New York, N. Y. 10020.

[4] Numbers in brackets designate References at end of paper.

cently, fundamental investigations of emulsions have been performed by scientists at Adelphi University, Penn State University, and Princeton University.

In the early 1970's, two French oil companies developed and marketed water/oil emulsion devices primarily to reduce particulate emissions. Compagnie Francaise de Raffinage (Total) manufactures a high pressure emulsion device which can be installed on most existing high pressure oil burners. The other French oil company is Elf Union, which manufactures an entire burner designed to fire emulsions.

Also, in the early 1970's, E. C. Cottell developed an ultrasonic emulsion device, commonly referred to as the Cottell reactor. It has recently received much publicity in the United States because of reports of improved combustion efficiency and air pollution reduction.

Other than the references previously mentioned very few detailed tests have been performed to determine the effect of emulsions on air pollutant emissions, and even fewer tests have been made to determine the effect on efficiency. Scherer and Tranie [5] reported test results in which particulate mass was carefully measured with the Total emulsifier, but little NO_x data and no efficiency data were obtained. For these reasons, EPA chose two commercially available emulsion devices for thorough testing, based on ease of installation and representative of two popular techniques for preparing emulsions, namely ultrasonic energy and high pressure mechanical energy. Tests were made with distillate and residual oils. The distillate oil test results have previously been reported [6] and the residual oil test results are discussed herein.

Experimental Methods

Analyzers. Gaseous emissions were measured with the following analyzers:

Gas	*Technique*
Oxygen (O_2)	Paramagnetic
Carbon Dioxide (CO_2)	Nondispersive infrared (NDIR)
Carbon Monoxide (CO)	Nondispersive infrared (NDIR)
Hydrocarbons (HC)	Flame ionization
Nitric Oxide (NO)	Chemiluminescence
Sulfur Dioxide (SO_2)	Photometric ultraviolet

Particulate mass measurements were made according to EPA Method 5 as published in the December 23, 1971 Federal Register. Particle size distribution was determined by using an Andersen Mark III cascade impactor with glass fiber substrates.

In order to avoid the inaccuracies involved in measuring steam quality at low pressure, a technique was used to measure change in efficiency, rather than actual efficiency. The steam generated by the boiler was passed through a heat exchanger, condensed, and returned to the boiler. The heat exchanger was cooled by a recirculating industrial water supply. By locking the control valve in an open position, the flow rate of the cooling water through the heat exchanger was monitored with a square-edged orifice and held constant. Thus, by measuring the temperature change across the heat exchanger, the change in efficiency from baseline to an emulsion test was obtained by using equation (1).

$$\Delta\text{Eff} = \frac{\Delta Te - \Delta Tb}{\Delta Tb} \quad (1)$$

Where: ΔEff = change in efficiency

ΔTe = temperature differential across heat exchanger when firing emulsion

ΔTb = temperature differential across heat exchanger under baseline conditions (firing oil only)

An estimate of actual efficiency was obtained by using the percentage of CO_2 and the stack temperature.

Equipment. The Cottell reactor consists of a premixing gear pump, the ultrasonic chamber, and associated plumbing. It emulsifies at low pressure and is adaptable to all types of burners. The unit tested was capable of operating within an oil flow range of 0.057 to 0.265 m^3/hr (15–70 gph). A crude emulsion is probably formed in the gear pump and is further refined as it passes through the ultrasonic chamber. The Cottell reactor operated on 115 V and drew a current of 5 A, thus requiring 575 W of power.

The Total emulsifier requires a pressure of 965 kPa (140 psi) or greater to operate properly, according to the manufacturer. Thus, its use is limited to high pressure burners. The tests were actually run at an oil pressure of approximately 2 MPa (300 psi). The device consists of two separate parts, a premixer and the emulsifier. The water and oil mix, and possibly form a crude emulsion, as they impinge in the premixer. The mixture is then pumped to the emulsifier which is located as close to the nozzle as possible. By changing parts on the premixer and emulsifier a range of oil flow rates can be fired.

A North American packaged Scotch boiler was used for all tests. It is rated at 2.64 GJ/hr (2.50×10^6 Btu/hr) with a maximum firing rate of 0.064 m^3/hr (17.0 gph) of residual oil.

Tests were run with constant oil flow rates, thus the total quantity of emulsion varied depending on the percentage of water in the emulsion. All tests with residual oil were run with a constant oil flow rate of 0.064 m^3/hr (17.0 gph). All data was taken under steady-state conditions, therefore, start-up and shut-down peaks were not included in the data.

Fuel. Tests were run with a low sulfur residual oil. Its properties were as follows:

Composition	
C	85.87 wt percent
H	11.85 wt percent
N	0.27 wt percent
S	0.89 wt percent
Ash	0.045 wt percent
Density	0.904 g/ml at 311 K (100°F)
	0.866 g/ml at 372 K (210°F)
Viscosity	0.076 Ns/m^2 at 311 K
	0.009 Ns/m^2 at 372 K
API gravity	22.0
HHV	44.45 MJ/kg (19,110 Btu/lb)
LHV	41.86 MJ/kg (18,000 Btu/lb)

Since residual oil has natural surfactants it was not necessary to add a surfactant to form a stable emulsion.

Emulsions. As mentioned previously the oil flow rate was constant and the total emulsion rate varied depending upon the percent water in the emulsion. During tests of the Cottell reactor emulsions were fired with 10, 15, 17.5, 20, 25, and 35 percent water. The air atomizing nozzle allowed a variety of emulsion rates to be fired. Tests with the Total emulsifier were more limited since a different high pressure nozzle had to be installed for each emulsion flow rate. During tests of the total emulsifier, emulsions were fired with 20 and 30 percent water. Thus, comparisons of data between the two emulsifiers must be qualified by the variance in methods of burner operation.

Results

Both the Cottell Reactor and the total emulsifier were tested on the Scotch packaged boiler under full load conditions. Measurements included NO, HC, SO_2, CO, CO_2, O_2, smoke, particulate (mass and size distribution), and change in efficiency. Since the HC emission level for this boiler is very low under baseline conditions, and there was virtually no change in HC level except at very low stoichiometric ratios, HC emissions are not reported or discussed. Likewise, SO_2 emissions remained virtually unchanged under all test conditions (approximately 525 ppm, corrected to 3 percent O_2) and are not reported.

Tests on both the Cottell reactor and Total emulsifier were run over a range of stoichiometric ratios for each emulsion tested. The best set of conditions (stoichiometric ratio and percent water in the emulsion) was then selected for particulate measurements.

Cottell Reactor Tests. It was found that smoke number de-

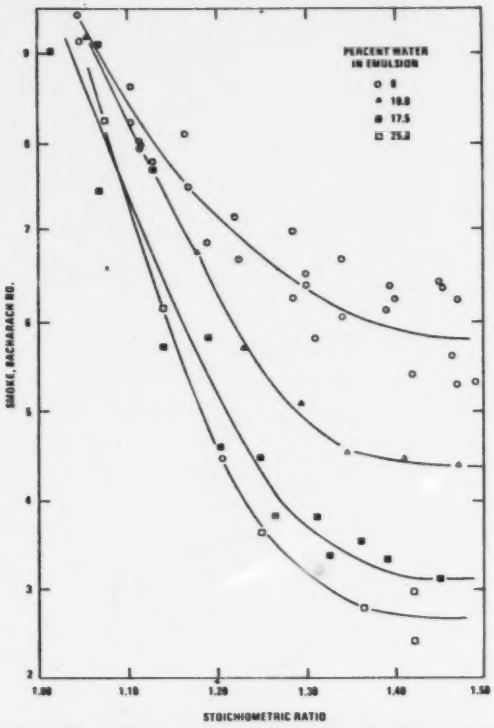

Fig. 1 Smoke emissions versus stoichiometric ratio for Cottell Reactor

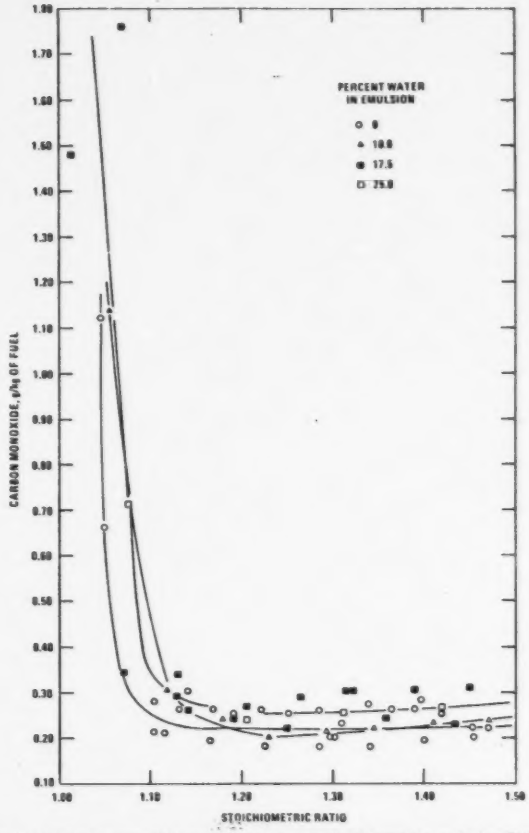

Fig. 3 Carbon monoxide emissions versus stoichiometric ratio for Cottell Reactor

creases as the percentage of water in the emulsion is increased. Fig. 1 shows the effect of stoichiometric ratio and percent water in the emulsion on smoke level. The highest smoke numbers, which leveled off at a Bacharach number of 5.8, were obtained under baseline conditions. As the percentage of water in the emulsion was increased the level of smoke dropped significantly. With 10 percent water a decrease of about a 1.5 Bacharach number occurred at a stoichiometric ratio of 1.40. When the percentage of water was increased to 15 percent (not shown) only a minor further reduction occurred, and the smoke leveled off at a Bacharach number of 4.1. The optimum smoke reduction of 45 percent occurred with 17.5 percent water in the emulsion. Beyond 17.5 percent water, the rate of smoke reduction decreased as additional water was added. The curve for 35 percent water (not shown) was only slightly better than that shown for 25 percent water. At low stoichiometric ratios the smoke level is high and similar for oil only and all emulsions. As the stoichiometric ratio is increased, the emulsions become increasingly effective in reducing smoke. Above a stoichiometric ratio near 1.4, no further decrease in smoke was observed for fuel oil or emulsions. Because 17.5 percent water appeared to give the optimum smoke reduction, this emulsion was chosen for the longer term particulate and efficiency tests.

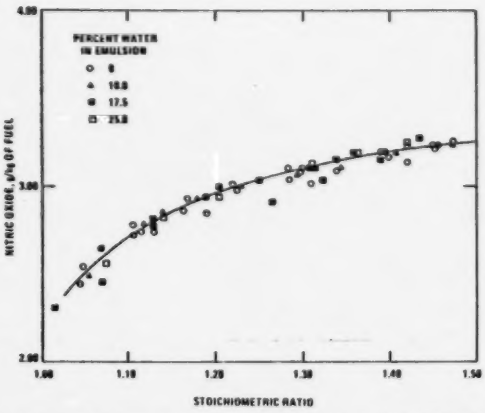

Fig. 2 Nitric oxide emissions versus stoichiometric ratio for Cottell Reactor

The level of NO emissions did not vary from baseline (oil only) for a given stoichiometric ratio when emulsions were fired, as shown in Fig. 2. This occurred due to the high fuel nitrogen content of the residual oil. Emulsions only affect thermally produced NO. Since NO emissions from fuels with high nitrogen content are primarily from the oxidation of nitrogen in the fuel, emulsions have little effect. However, the NO curve does decrease as the stoichiometric ratio is decreased. If one chooses to operate at a lower stoichiometric ratio, which is possible because of the reduction of smoke level, the NO level could be reduced. With a 17.5 percent emulsion a maximum NO reduction of 9 percent was achieved when the stoichiometric ratio was reduced to 1.17 which produced a Bacharach smoke of 5.8 (equivalent to baseline (oil only) smoke levels at a stoichiometric ratio of 1.45).

As shown in Fig. 3, CO levels did not vary significantly when emulsions were fired. The CO level for 17.5 and 25.0 percent emulsions was approximately 20 percent higher than for fuel oil, but at these low levels that is not considered significant.

In Fig. 4, particulate mass is plotted versus percent water in the emulsion for two constant stoichiometric ratios. Each point shown

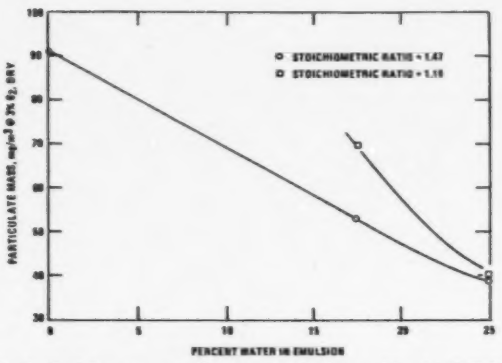

Fig. 4 Particulate mass versus percent water in emulsion for Cottell Reactor

Table 1 Efficiency change comparison for the Cottell Reactor firing a water/residual oil emulsion (for a 5.8 Bacharach smoke spot at steady-state conditions)

Percent Water in Emulsion	Stoichiometric Ratio (for No. 5.8 smoke spot)	ΔT Across Heat Exchanger, K	ΔT Across Heat Exchanger, °F	Efficiency Change Indicator (%)
0.0	1.45	24.44	44.00	-----
10.0	1.23	24.58	44.25	+0.57
15.0	1.20	24.66	44.39	+0.89
17.5	1.17	23.86	42.95	-2.39
20.0	1.16	23.67	42.60	-3.18
25.0	1.15	23.31	41.95	-4.66

represents the average of three test runs. As the percentage of water increases, the mass of particulate decreases significantly. With low percentages of water in the emulsion the particulate mass emissions for the high stoichiometric ratio curve is much less than the curve for low stoichiometric ratios. However, the two curves begin to converge as the percentage of water in the emulsion is increased.

Fig. 5 provides an indication of the effect of increasing the percentage of water in the water/residual oil emulsion for a constant stoichiometric ratio. If data were plotted for a different stoichiometric ratio the curves would differ somewhat from those shown. A stoichiometric ratio of 1.45 was chosen because the baseline smoke curves leveled off at that point. As the figure shows, an increase in the percentage of water had no effect on NO, smoke decreased significantly, and CO increased by a small amount.

The effect on efficiency of water/residual oil emulsions produced by the Cottell reactor is shown in Table 1. For a basis of comparison, the minimum smoke number obtainable with oil only (5.8 Bacharach No.) was used. By using this technique the stoichiometric ratio varied for baseline (oil only) and each emulsion, but this allowed efficiency improvement from using less excess air to be included in the analysis.

As shown in Table 1 from the bulk of the data, the maximum increase in efficiency of slightly less than 1 percent occurred with 15 percent water in the emulsion. In later tests, run to confirm these data, efficiency change indicators of +1.16 and +1.68 occurred when firing an emulsion with 15 percent water. This shows that the actual change in efficiency may vary to some extent depending on exact test conditions, but the magnitude of change is known.

Even though actual efficiency was not measured, an estimate was obtained based on the CO_2 percent and temperature of the flue gas. At baseline conditions the stoichiometric ratio was 1.45, the CO_2 was 10.4 percent and the net stack temperature was 439 K (331°F). The estimated baseline boiler efficiency was 85.5 percent.

The data in Table 1 suggest that emulsions provided improved atomization which allowed operation at lower stoichiometric ratios. This would explain the improvement in efficiency with 10 and 15 percent water emulsions. Beyond 15 percent water the heat lost to vaporization of the additional water was greater than the gain from improved atomization.

Another factor which could affect efficiency over a long term period of time is particulate loading. Since operation with emulsions prepared by the Cottell reactor decrease particulate mass emissions and smoke number, it is likely that fewer deposits would occur on the heat transfer surfaces of the boiler. Therefore, after a period of time the efficiency of a boiler firing a water/oil emulsion probably would not decrease as rapidly as with the same boiler firing oil only. Stack temperature data taken over a three day period with and without an emulsion prepared by the Cottell reactor confirms this trend. Hopefully, data presently being collected by private industry and other government agencies will provide more information about long term effects.

Total Emulsifier Tests. Results obtained from the Total emulsifier water/residual oil emulsion tests were different from those described for the Cottell reactor. Also, as mentioned previously, the method of atomization was different. As shown in Fig. 6 the smoke increased from a baseline (oil only) level of 3.6 Bacharach number (at a stoichiometric ratio of 1.45) to 4.4 when a 20 percent water emulsion was fired. As the water percentage was increased to 30 percent the smoke level dropped to 2.8, which is significantly lower than baseline.

The effect of Total emulsions on NO emissions is shown in Fig. 7. There is little difference among the curves, but the data do suggest a very small NO reduction with the 20 and 30 percent water emulsions. Because of the fuel nitrogen effect discussed previously, it is likely that the reduction shown is actually due to data scatter, and is probably not real.

Fig. 8 shows the effect of Total emulsions on CO emissions. The 20 percent emulsion was lower than baseline for stoichiometric ratios above 1.40, but for lower stoichiometric ratios the CO was much higher. With 30 percent water the CO emissions were consistently lower than baseline. The baseline CO emission level for high pressure atomization was double that of air atomization.

The effect of Total emulsions on particulate mass emissions is shown in Fig. 9. The emulsions resulted in significant reductions. The baseline particulate mass was 173.5 mg/m³ at 3 percent O_2, dry compared to 65.0 mg/m³ with 20 and 30 percent water emulsions. It should be noted that the baseline particulate level for high pressure atomization is much higher than baseline for air atomization (91.0 mg/m³) as shown in Fig. 4.

The affect of increasing the percentage of water in water/residual oil emulsions for a constant stoichiometric ratio is shown in Fig. 10. The CO level decreases as the percentage of water is increased,

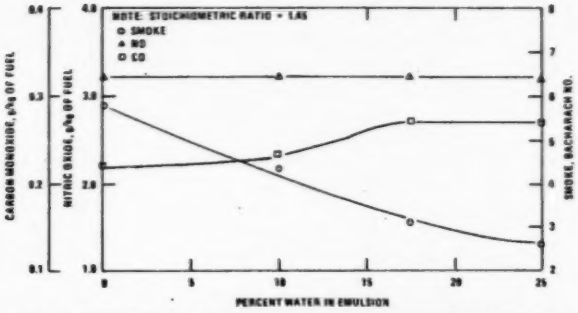

Fig. 5 Emissions versus percent water in emulsion for Cottell Reactor

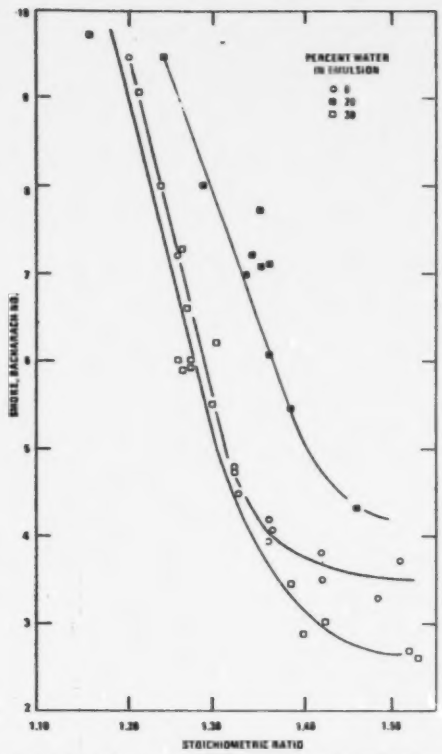

Fig. 6 Smoke emissions versus stoichiometric ratio for Total emulsifier

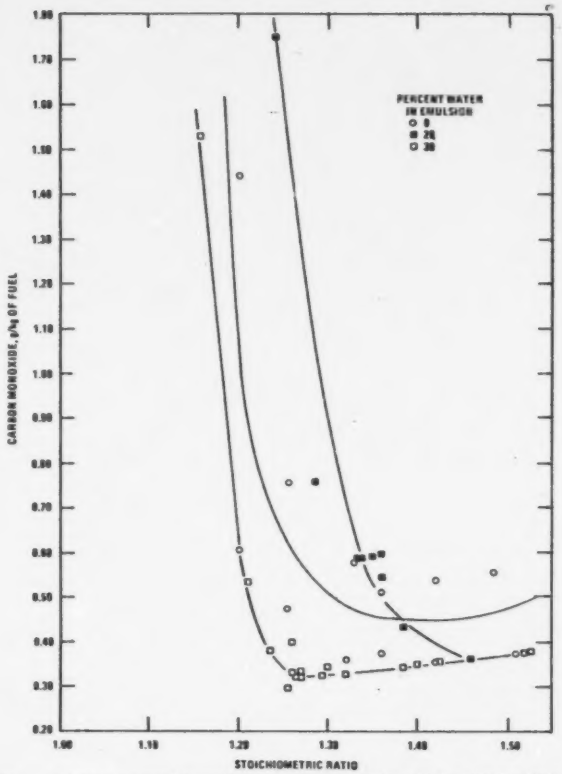

Fig. 8 Carbon monoxide emissions versus stoichiometric ratio for Total emulsifier

but when compared to baseline for air atomization (Fig. 5) the baseline CO level for high pressure atomization is twice as high. Again, Fig. 10 shows there is virtually no effect on NO emissions with water/residual oil emulsions. The Total emulsion smoke curve is most interesting. As the percentage of water is increased to 20 percent, the level of smoke increases, but as water is increased above 20 percent the smoke decreases. However, Fig. 9 shows that particulate mass decreases from zero to 20 percent water and levels off or increases as the amount of water is further increased. The two curves have inverse relationships. This occurred because smoke is an optical (reflectance) reading which is affected by particulate mass and particle size distribution. With the Total emulsifier, particulate mass decreased which would cause smoke to decrease if the particle size distribution remained constant. However, the particle size distribution shifted to a smaller size range. Since small particles scatter light more than larger particles, the level of reflectance was decreased and a higher smoke number resulted.

The effect on efficiency of water/residual oil emulsions produced by the total emulsifier is shown in Table 2. For a basis of comparison the minimum smoke number obtainable with the highest smoke curve (20 percent water in the emulsion) was used. By using this technique the stoichiometric ratio varied for each emulsion and baseline (oil only), but this allowed efficiency change due to excess air to be included in the analysis.

As shown in Table 2, the maximum increase in efficiency of nearly 2 percent occurred with 20 percent water in the emulsion. With 30 percent water in the emulsion efficiency decreased from baseline by 4.4 percent.

Even though actual efficiency was not measured, an estimate was obtained based on CO_2 percent and flue gas temperature. At baseline conditions, the stoichiometric ratio was 1.45, the CO_2 was

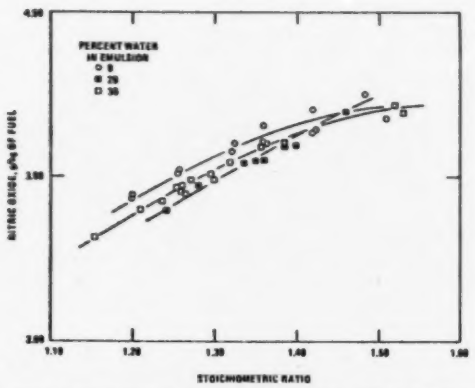

Fig. 7 Nitric oxide emissions versus stoichiometric ratio for Total emulsifier

Table 2 Efficiency change comparison for the Total emulsifier firing a water/residual oil emulsion (for a 4.3 Bacharach smoke spot at steady-state conditions)

Percent Water in Emulsion	Stoichiometric Ratio (for No. 4.3 smoke spot)	ΔT Across Heat Exchanger K	°F	Efficiency Change Indicator (%)
0.0	1.340	21.67	[illegible]	-----
20.0	1.460	22.06	39.70	+1.79
30.0	1.325	20.71	37.28	-4.41

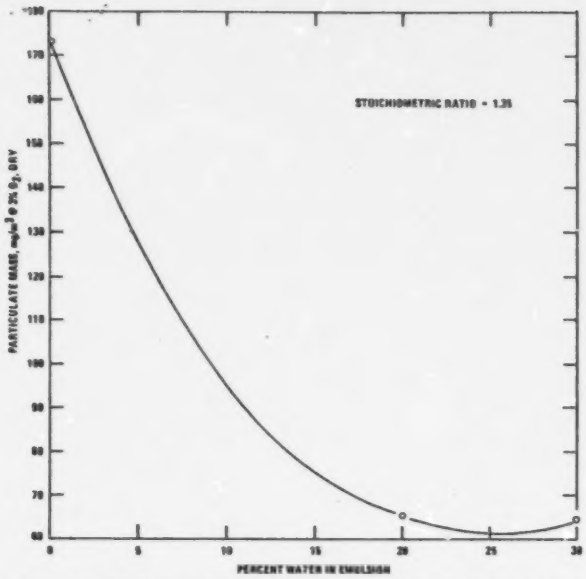

Fig. 9 Particulate mass versus percent water in emulsion for Total emulsifier

10.6 percent, and the net stack temperature was 432K (318°F). The estimated baseline boiler efficiency was 85.5 percent.

Conclusions

In this test series water/residual oil emulsions were formed by two different mechanisms, low pressure mechanical and ultrasonic energy (Cottell reactor) and high pressure mechanical energy (Total emulsifier), and were fired into a commercially available packaged Scotch type boiler at a constant oil flow rate. Due to the different atomization techniques employed by the two emulsifiers, the baseline results differed. Also, different results were obtained with each emulsifier. This shows that the method of emulsion preparation is important with water/residual oil emulsions.

In general, water/residual oil emulsions from both emulsifiers had little or no effect on emissions of NO, SO_2, and HC. With the Cottell reactor CO was increased slightly as the percentage of water was increased. With the Total emulsifier CO emissions were lower than baseline (oil only) for stoichiometric ratios at which the boiler would normally be operated; however, it should be noted that CO emissions were higher with high pressure atomization than air atomization under baseline conditions. Both emulsion devices reduced particulate mass, but the Cottell reactor emulsion achieved the lowest levels. Smoke consistently decreased as the percentage of water was increased with the Cottell reactor, but with the Total emulsifier the smoke number increased as water was increased from zero to 20 percent, and decreased as water was further increased to 30 percent. This was due to a shift in particle size distribution to a smaller particle size range with the Total emulsifier. Both emulsifiers provided a small improvement in efficiency under certain conditions. The optimum percentage of water in the emulsion for thermal efficiency improvement and reduced emissions may vary depending on boiler/burner design. Also, the effect of emulsions on efficiency and air pollutant emissions may vary from unit to unit.

It should be emphasized that the results of these tests apply only to residual oil. Tests were also run to determine the effect of water/distillate oil emulsions on emissions and efficiency. The results, which were not the same as with water/residual oil emulsions, were discussed in a previous publication [6].

Acknowledgments

It is my pleasure to acknowledge the assistance of George R. Gillis, EPA's Engineering Technician who performed the emulsifier tests.

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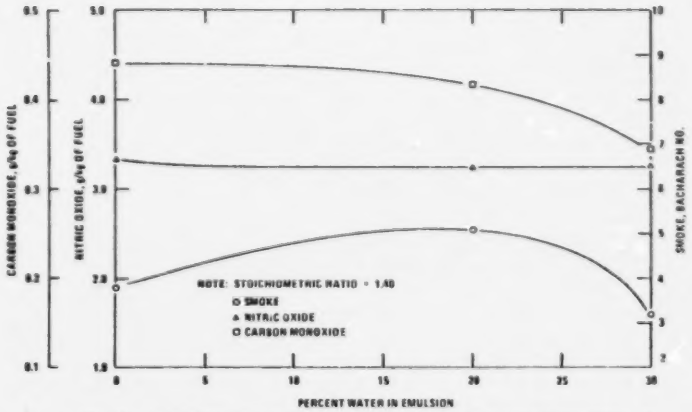

Fig. 10 Emissions versus percent water in emulsion for Total emulsifier

DISCUSSION

F. L. Dryer[5]

In recent months, the addition of water to combustion systems has been the subject of numerous articles in the popular literature [7–12].[6] This renewed interest has been stimulated by the invention of several "devices" for producing water-in-fuel emulsions, primarily for combustion in external systems, and by the claims of one of the inventors E. C. Cottell [13] that the use of his device provides major improvements in both emissions and energy utilization characteristics of practical combustion systems.

While several industrial evaluations have been mentioned in these articles and a more limited number of technical papers have been presented at various meetings [14, 15], the works of Hall appear to be the first external combustion results on water-in-fuel emulsions to be published in the open literature. Hall is also the first to have attempted complete documentation of both emissions characteristics and effects on energy utilization efficiency. However, intensive review of the subject [16–18] has led me to conclude for reasons summarized below that this work, as do other known results, falls short of quantitatively documenting the optimal combustion modifications achievable with the use of water-in-fuel emulsions. The preceding paper of this session [19] amply demonstrates that a number of relatively simple modifications of existing burner systems can also lead to similar improvements in carbon particulate emissions and thermal operating efficiency reported here. Thus, the question of what combustion of water-in-fuel emulsions accomplishes that cannot be done more economically through modification and/or adjustment of existing burner hardware remains unanswered.

The principal factor distinguishing the combustion of water-in-fuel emulsions from water addition through other means is a phenomenon termed "microexplosions" by those who first discovered it nearly twenty years ago [20]. Microexplosions such as those documented in Fig. 11 are a result of preferential vaporization of small water droplets dispersed within the fuel (internal phase). It is theorized that a properly formulated emulsion will produce microexplosions of sufficient violence to produce secondary atomization and micro-mixing within a spray of emulsified fuel droplets, thus reducing the level of heterogeneity that exists in most liquid spray combustion systems. Through mechanisms described elsewhere [17] microexplosions, therefore, reduce formation of large particulates and thermal NO_x. The additional benefit of localized charge dilution *within* the fuel rich region of the diffusion (mixing) limited combustion is also of significant consequence to reducing thermally formed NO_x and *gas phase* soot formation, and combined with the effects from the micro-explosions themselves, the process leads to improved emissions/utilization characteristics of the particular combustion system. Unfortunately, in contrast to internal combustion applications [17], addition of water to external combustion must result in an additional loss mechanism due to the efflux of the vaporized water (heat of vaporization) from the device. Without reduction in other losses, water-in-fuel combustion in external systems must therefore lead to decreases in thermal operating efficiency. However, reduced formation of carbon particulates (especially those of larger size) leads to decreases in the excess air required to meet the desired particulate emissions level. Thus, it is the functional dependence of the amount of water added to emissions levels and excess air required which primarily governs the magnitude and sign of changes in thermal operating efficiency. Previous investigators have not only recognized this fact, but furthermore have tacitly assumed that the internal phase ratio (volume percent of water in the emulsion) is the only emulsion parameter important in optimizing emulsion combustion characteristics.

However, theoretical and experimental work at Princeton [21] has identified several other emulsion properties which must also be taken into account. First, it would appear that not only the amount of water, but the way it is distributed within the fuel droplets is important to optimizing the microexplosion phenomena (internal phase size distribution). The rates of heating and of phase change as well as the total volume change during vaporization are all important phenomena to be considered in selecting the correct internal phase properties. Confirming evidence for these hypotheses are currently available from at least two sources.

1 Current results of suspended droplet combustion tests at Guggenheim Laboratories indicate that by decreasing the internal size distribution of a water-in-Bunker C fuel emulsion from approximately 10 microns to around 1 to 2 microns significantly increases the time necessary to totally disrupt the primary fuel droplet.

2 A recent study [22] of the effects of emulsified fuel combustion on particulate emissions and primary zone radiation from a gas turbine combustor has shown that both the level of water content and surfactant loading of the emulsion have substantial effects on emissions reductions (Figs. 12 and 13).

The emulsions were formed using a Gaulin Model 110 Laboratory homogenizer operating at a constant pressure of 3000 psi. It was initially documented that addition of surfactant to the JP-5 reference fuel without water showed no effect on combustion emissions. At low surfactant concentrations, the stabilized internal dispersed phase size distribution reaching the combustor was determined by surfactant loading because there was an insufficient amount to support the total interfacial area of the internal phase size distribution produced at the homogenizer. As surfactant concentration was increased, larger interfacial areas could be supported and smaller internal phase size particles were produced. The curves of emissions approach assymptotic values at increased surfactant loading because the internal phase size distribution is then governed by the homogenization pressure. If homogenization pressure had been increased internal size distribution may have been further reduced. It is reasonable to suggest that at very small internal particle sizes such as those found in microemulsions [23], the material would behave as a multicomponent solution and the microexplosion phenomena would become insufficient to rupture the primary fuel droplet structure.

Contrary to the postulates of others [24], Fig. 13 suggests total flame radiation is reduced rather than increased by using emulsified fuels. Toussaint and Heap [15] also have reported similar observations for furnace combustion. Reduction in radiation is not surprising, since in diffusion (mixing) limited combustion continuum radiation from particulates is far more significant than spectral radiation from hot combustion gases.

From the patent literature [25, 26] it appears that neither manufacturer of the devices tested has considered any emulsion characteristics other than having the dispersed phase droplet size small in comparison to the atomized emulsion spray. It should also be noted that the TOTAL device depends on ultrasonic rather than high pressure mechanical effects to produce an emulsion. The ultrasonic energy produced by cavity/orifice plate resonance is probably of much lower intensity than that of the Cottell reactor. Yet, from fundamental principles, there appears to be no energy limit which if surpassed permits emulsion stability for long periods of time without the aid of chemical stabilizers. Residual oils themselves contain sufficient amounts of natural emulsifying agents for stabilization at room temperatures. However, once the energy necessary to form the emulsion is provided, the internal size distribution which is stabilized may only be modified by changing the amount of chemical emulsifying agent. Furthermore Barrett, et al. [27] have noted partial phase separation (breaking) of some natural residual oil emulsions at elevated temperatures well below the preheat levels used by Hall.

While not reported in the paper, Mr. Hall has stated in private communication that fuel oil and water preheats were held constant upstream of the emulsifying devices at 190 and 140°F, respectively. Thus emulsion preheat decreased from that of the pure fuel as larger

[5] Research Staff and Lecturer Guggenheim Laboratories, Princeton University, School of Engineering and Applied Science, Princeton, N. J.

[6] Numbers in brackets designate Additional References at end of discussion.

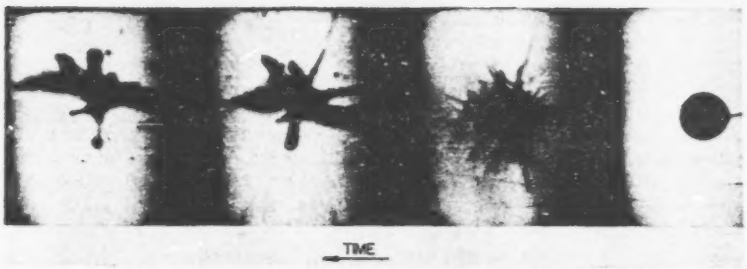

Fig. 11 16 mm high speed cinematography sequence of a burning droplet of 22 percent water-in-bunker C fuel emulsion (no added surfactant). Quartz filament (18μ) suspended droplet ignited with a small butane/air pilot flame. Initial droplet size, 350 microns. Internal phase *mass mean* size distribution approximately 10 microns. Camera framing rate, 5000 frames per s. Performed at Guggenheim Laboratories, Princeton University, Princeton, N. J. (Entire high speed film shown during oral discussion of this paper.)

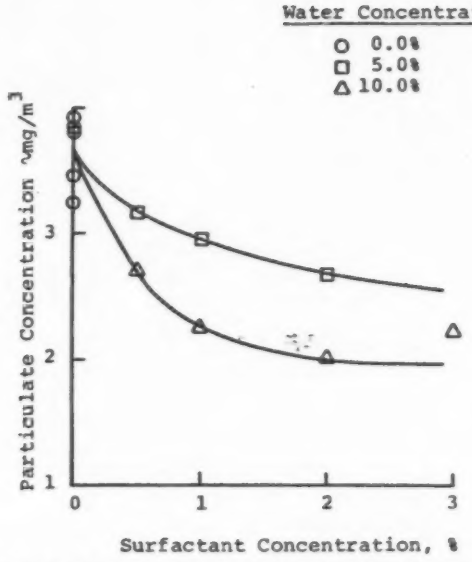

Fig. 12 Summary of effects of emulsion characteristics on the exhaust particulates at full power conditions for an Allison T-63 Gas Turbine Combustor—from reference [22]

internal phase ratio emulsions were formed.

Barrett, et al. [27] and Scherer and Trainie (reference [5]) have documented that the viscosity of water-in-fuel oil emulsions is considerably larger than that of the pure fuel, and is a function of internal phase concentration. Thus, Barrett, et al., concluded that fuel preheat temperature of residual emulsions must be increased to assure identical primary atomization for emulsions and pure fuel. Without such an adjustment secondary atomization from microexplosions must overcome reductions in primary atomization before any benefits can be realized. That changes in primary atomization of the order of magnitude which must have occurred here can cause substantial effects on particulate emissions was documented in a previous paper of this session. [19] It should be noted that according to Mr. Hall, no instructions suggesting the required variation in preheat were offered by the manufacturers of the devices tested.

In summary, because of the limitations in testing procedures and characterization of the emulsions, one must consider this work as a product evaluation rather than a quantitative study of the combustion characteristics of water-in-residual fuel emulsions. In this context, Mr. Hall has produced a reasonable evaluation of two devices currently commercially available specifically for producing emulsions for combustion. However, a performance comparison of the devices must be further qualified by the variance in atomizer design used with each emulsifier.

It is not possible from these data to determine the minimum water required in emulsion to optimally effect the external combustion of conventional residual fuels. Some recent preliminary data [28] suggest that levels as low as 5 percent (by volume) may be sufficient. Thermal operating efficiency improvements may be several times those reported by Mr. Hall. However, it is clear from both Hall's data and

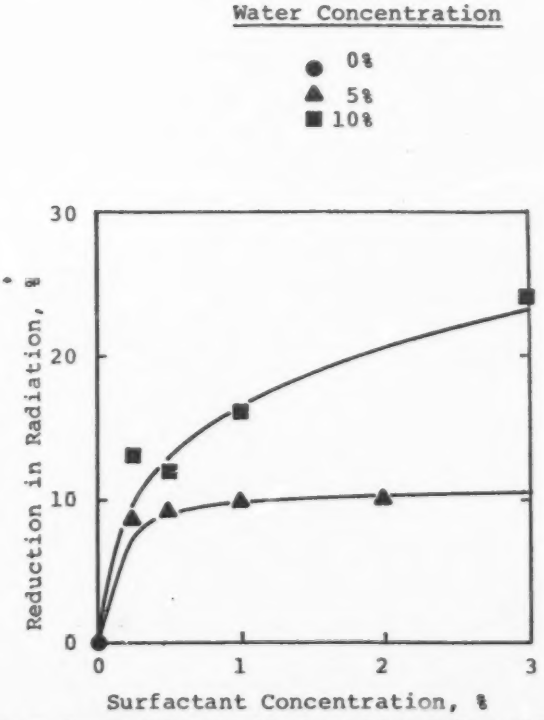

Fig. 13 Summary of effects of emulsion characteristics on the flame radiation at full power conditions for an Allison T-63 Gas Turbine Combustor—personal communication, Dr. C. A. Moses, US Army Fuels & Lubricants Laboratory Southwest Research Institute, San Antonio, Texas

fundamental principles that improvements as large as 20 percent (absolute) are impossible unless the external combustion system was initially operated far from optimum conventional design.

That simultaneous reduction of particulates and thermally produced NO_x can be achieved with emulsion combustion with improvements in thermal operating efficiency is a unique characteristic of emulsion combustion and deserves further research. Yet, perhaps the more intriguing prospect lies in simultaneous application of staged combustion and emulsified fuel technology. One might, thus, alleviate both fuel and thermally produced NO_x as well as particulates without increase in excess air requirements or degradation in thermal operating efficiency.

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20 Reference [1] this paper.

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22 Moses, C. A., "Reduction of Exhaust Smoke From Gas Turbine Engines by Using Fuel Emulsions," Paper No. 75-18; presented at the Western States Section Meeting of the Combustion Institute, Palo Alto, Calif., Oct. 20, 21, 1975.

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24 Dooher, J., et al., "Emulsions as Fuels," ASME paper No. 75-WA/FU-3, presented to the Fuels Division of the ASME, Winter Annual Meeting, Houston, Texas, Dec. 3.

25 Patent No. 3,809,372, "Devices for the Generation of Ultrasonics and Their Application to the Preparation of Emulsions," Assignee Companie Francaise De Raffinage, Paris, France, May 7, 1974.

26 Patent No. 3,749,318, "Combustion Method and Apparatus Burning an Intimate Emulsion of Fuel and Water," E. C. Cottell, July 31, 1973.

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28 Personal Communication, R. Kinney, Gardin Corporation, Everett, Mass.

U. Bonne[7]

This discussion is going to focus on three aspects of energy and operating cost savings due to external combustion of fuel oil-water emulsions:

1 those discussed in Mr. Hall's paper;

2 energy savings predicted via flue loss method;

3 recommended future work.

1 As a result of Mr. Hall's study, no doubt remains that emulsions reduce the emission of particulate mass loading of flue gases, in spite of relatively small changes in NO (total NO_x not given), CO and hydrocarbons. However, the energy savings of adding water to hydrocarbon fuels in external combustion systems are expected to be low, since volumetric expansion or generation of mechanical work, as in internal combustion engines is not the issue. Exact definition of the reduction of energy consumption or boiler operating costs, although beyond the main emphasis of the study, can, to some extent, be derived from the provided data, of which Table 3 provides a brief summary and clarification. The purpose of emphasizing this here stems from the belief that this is necessary information to anyone considering implementing the use of emulsified fuels. The author chose to adjust the combustion air, after adding the water, to match the Bacharach smoke number rather than the smoke mass loading. This is why the combustion air had to be increased with the Total device, leading to an increase in excess air losses and a decrease in particulate mass losses. Table 3 shows how large the efficiency gains and fuel savings would be according to the author, rows 15 and 16.

2 The provided data can, on the other hand, be used to arrive at efficiency gains by analyzing the change in flue loss component. Fig.

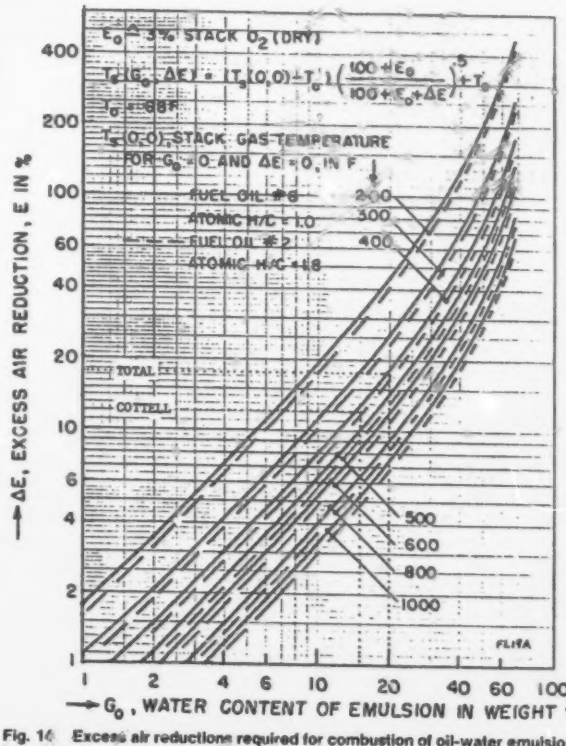

Fig. 16 Excess air reductions required for combustion of oil-water emulsion fuels in order to maintain equal combustion efficiency with respect to fuel oils alone—temperature reduction credit included

[7] Honeywell Inc. Corporate Research Center Bloomington, Minn.

Table 3 Comparison between Cottell and Total Emulsifiers. North American packaged Scotch boiler rated at 2.64 GJ/hr ($2.50 \cdot 10^6$ Btu/hr) and fired at 97.5 percent of rating. Residual fuel oil of 44.45 MJ/kg (19,110 Btu/lb) HHV.

Parameters	Units	Emulsifiers: Cottell	Emulsifiers: Total
Baseline			
1 Combustion air, A/flue CO_2	% of stoich./%	145/10.4	136/10.6
2 Flue gas temperature net rise	F	331	318
3 Flue losses (recalculated)	%	15.58/ 15/75	14.67/15.20
4 Particulates: Mass loading	mg/m^3	91@A = 147	173@A = 135
5 Bacharach No.		5.6@A = 145	4.7@A = 134
6 Combustion Air	% of stoich.	120	146
7 Flue gas temp. net rise(1)	F	318	338
8 Particulates: Mass loading	mg/m^3	60@A = 147	66@A = 135
9 Reduction to	%	63@A = 147	38@A = 135
10 Reduction to	%	84@A = 119	
11 Bacharach No.		5.6@A = 120	4.3@A = 146
Optimum Emulsion at water content	wt %	15	20
12 Emulsifier power consumption	watts	575 cos ϕ*	?
13 Prime fuel rate equiv.	% of fire	.222	
14 Relative costs (2x prime fuel)	% of fire	.444	
15 Efficiency gain	%	.89—1.68	1.79
16 Fuel savings	%	1.05—1.98	2.11
17 Operating cost savings	%	.61—1.54	<2.11
18 Max. cost of emulsification equipment for 3 year payback (no interest)	$	382—965	<1322
Efficiency gain due to changes in:			
19 Fuel water content	%	−1.10	−1.57
20 Combustion air	%	1.43	− .59
21 Flue temperature rise	%	.39	− .57
22 Particulate mass	%	≃ .01	≃ .2
23 Total	%	.73	−2.53

*a value of cos ϕ = .8 was assumed.

14[8] shows a family of curves corresponding to the amount of combustion air reduction, for the amount of water in the emulsion, required to maintain efficiency constant. Fig. 14 is based on the finding[9] that at constant firing rate (Btu/hr), increases in the water content of emulsions does not lead to increases in flue temperature. Fig. 14 can be of help to determine when to use or not to use emulsified fuels. A simple enthalpy balance calculation shows that air reductions required to break even under the conditions of Hall's experiments are 12 and 17.7 percent, respectively, as shown in Fig. 14. A breakdown of the changes in flue loss components due to fuel water content, excess air, flue temperature changes,[9] and particulate mass are listed in Table 3, rows 19–22. The sum of these (row 23) should agree with row 15. As shown, good agreement is obtained only for one set of data.

3 It appears that more experimental data on the reduction in excess combustion air achievable as a function of (emulsified) water additions and emulsification equipment are needed in order to more completely assess the benefits, describe the effect of water droplet size in the emulsion, and pinpoint the optimum operating conditions. Work underway at PrincetonUniversity[10] and consideration of hardware alternatives such as conventional homogenizing equipment[10] should provide interesting new insights. Water droplet sizes in the emulsions were not measured in the present study but it appears that pressure atomization resulted in larger soot particles, but similar combustion efficiencies, if the two devices had been operated on the basis of equal mass loadings, corresponding to similar combustion air in the pure fuel runs. Another aspect of this picture will be provided by the measurements of the long term effect of fouling of heat transfer surfaces. Operating boilers at equal flue particulate mass loadings but reduced particle size (due to the effect of the emulsion) may well reduce the rate of soot deposits and I am looking forward to the results of the work Hall said is under way.

Author's Closure

Dr. Dryer stated that "this work, as do other known results, falls short of quantitatively documenting the optimal combustion modification achievable with the use of water-in-fuel emulsions." This statement is true but it is not germane to the EPA study since the purpose was to evaluate the effect on emissions and efficiency of two commercially available water/oil emulsion devices. The fact that the manufacturers of these devices did not optimize the emulsifiers is not the fault of the EPA. It was not the intent of this study to develop a commercially available product for a manufacturer. A more fundamental study of the water/oil emulsion process would be useful and may result in some further reduction of particulate mass emissions and may provide some additional increase in efficiency. The subject study does give the direction of change and a reasonable idea of the magnitude, as was intended.

In reference to Dr. Dryer's comment about the need for surfactants to produce a stable emulsion, tests were run using the Cottell Reactor and the Total emulsifier without surfactants. If there was a phase separation it did not affect the combustion process to any noticeable degree. Our experience has shown that surfactants are only necessary when firing distillate oil. Also, the use of surfactants was not recommended by either manufacturer for firing water/residual oil emulsions.

Dr. Bonne stated that he is looking forward to the results of work by industry and other government agencies in which an evaluation is being made on the effect of emulsions on efficiency for a long term due to reduced particulate deposits on heat transfer surfaces. Unfortunately, one such test which was being conducted by the Department of Defense has been cancelled due to equipment problems.

In Table 1 of Dr. Bonne's discussion in item 18, the "maximum cost of emulsification equipment for 3-yr payback (no interest) for the Cottell Reactor appears low and the figure listed for the Total emulsifier appears much too high. According to Crest Ultrasonics the Cottell Reactor tested by EPA costs 5500 dollars plus an installation charge. This includes a guarantee on parts and service for 1 yr. According to D. S. Volkmar, the Total emulsifier is not an "off-the-shelf" commercially available item but can be specially ordered from Compagnie Francaise de Raffinage for less than 500 dollars.

[8] Bonne, U., "External Combustion of Fuel Oil-Water Emulsions," Honeywell Inc., CRC, Apr. 14, 1975; to be presented at 1976 ASHRAE Annual Meeting, Dallas, Texas, Feb. 1976.

[9] Hall, R. E., EPA, private communication, Mar. and Nov. 1975.

[10] Dryer, F. L., Princeton University, private communication, June 1975.